4 On scale problems in modelling: an example from soil ecology

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4.1 Introduction

Agricultural research aims to increase our understanding of systems and to reveal manipulable characteristics at the farm scale, so that management practices can be improved. Because agricultural systems are too complex to understand as a whole, subsystems (e.g. soil, plant, microclimate) and subprocesses (e.g. transport processes, photosynthesis, energy balance) are distinguished (Figure 19) and studied (systems analysis) with the ultimate objective of interconnecting the resulting knowledge and of returning to the farm scale (systems synthesis). Subsystems and subprocesses usually operate on much smaller spatial and temporal scales than the total system: they represent a different level of organization than the farm level.

For example, crops in the Netherlands usually have a fairly homogeneous appearance on a hectare scale, indicating the integrative power of the root–soil system with respect to space and the homogenizing effect of soil tillage and fertilization. For the crop growth process the characteristic time in which a substantial change in amount of biomass occurs, i.e. the time coefficient, is of the order of a week. Soil oxygen concentration, however, which may have a pronounced influence on crop growth (Drew, 1983), is known to vary substantially at a

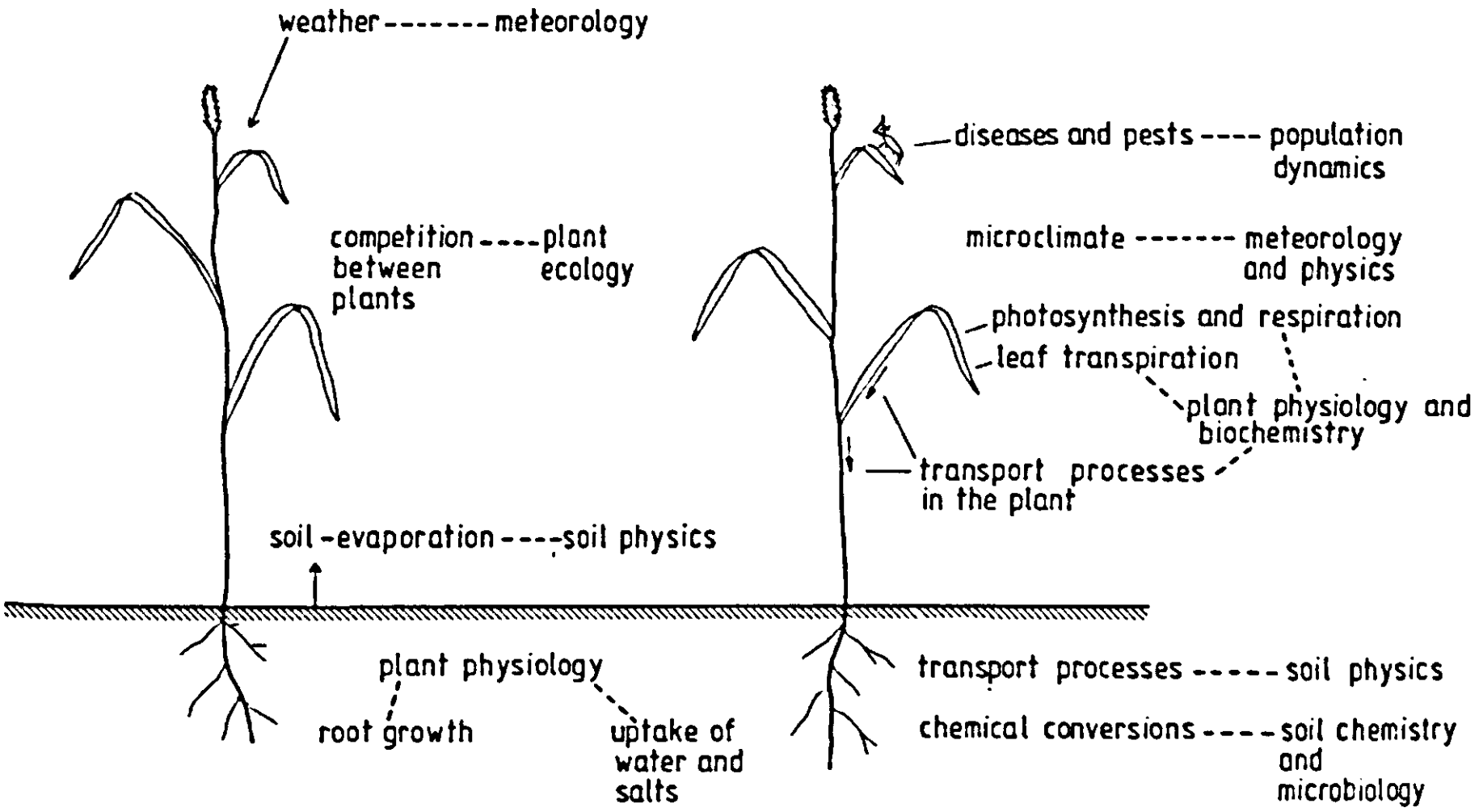

Figure 19. A crop system and some subsystems and processes that may be distinguished for its study (Source: de Wit, 1982b).

millimetre scale in the soil, i.e. at the root scale. Oxygen distribution quickly reacts to events such as rain or ploughing: its time coefficient is less than hours.

Such different levels of organization confront us with a general problem of applying the systems analysis and synthesis approach to complex systems, namely how many levels of organization can or should be bridged to combine an optimal causal insight in the system with the possibility of returning to the desired level of organization? In other words: to what level of detail should problems be analysed and studied to move forward in research without losing contact with the highest level of organization that should ultimately be reached? A factor that complicates the problem is that models remain simplified representations of reality. Different models of the same system may thus be developed and a puzzling question is: are there rules on how a system should be represented? De Wit (1968; 1970) was probably the first to focus attention on these problems from an agricultural point of view.

The general importance of the problem is beyond dispute, since each researcher is faced with it in each new modelling study. The scale problem and related questions cannot be answered simply. Instead, they should be discussed and each study means that new compromises need to be found. The following aspects need to be coherently considered, to clarify the problem of scale:

- objective of the study
- level of organization or scale of processes
- availability of theories
- possibility of clearly defining subsystems
- possibility of validating the model of a system
- possibility of returning to the field level of organization in the systems synthesis phase.

In this paper some aspects of these problems of modelling and related questions will be explored, using the soil ecology process of aeration and denitrification as illustration.

4.2 Objective of the study

The objective of a study is the first determinant of what level of organization will be studied. For example, the objective of a soil ecology study I carried out on aeration and denitrification* (Leffelaar, 1986; 1988) was to integrate knowledge about the major processes that cause and affect denitrification in unsaturated soil, by modelling and experimentation. This objective indicates that an explanatory simulation model interconnecting different spatial and temporal scales of organization was aimed at: the overall spatial scale is in the order of one to ten centimetres which is the level of soil aggregates, whereas the oxygen concen-

* Denitrification denotes the process of nitrate reduction to molecular nitrogen under anaerobic conditions by heterotrophic microbes via the intermediates nitrite and nitrous oxide, resulting in losses of (fertilizer) nitrogen from the soil.

tration varies from 21 to 0% within a few millimetres when soil is water-saturated. The time coefficients for the biological processes of respiration and denitrification, for water flow and for gas diffusion flows, range from about 24 h to 60 s. Causal relationships were sought, rather than a direct answer to how much nitrogen was lost from soil per hectare.

If the latter had been the objective, it would have been better and faster to measure these gaseous losses directly in the field. Such experimental results would, however, apply uniquely to the site of the measurement and would not be general: there would be hardly any possibility of extrapolating the results. In causal studies, generality is contained in the model structure, as expressed by the differential equations and the feedbacks, whereas specificity is introduced by the parameters.

4.3 Level of organization or scale of processes

The level of organization or the scale on which a process occurs is another determinant of how that process should be studied. For example, microbes have a typical dimension of one μm^3 and they work on the pore scale in soil. Their numbers amount to 10^7 to 10^9 per g soil (Alexander, 1977). Because of these large numbers, one might at first sight expect a homogeneous distribution of microbes over the available soil surface area. This is not the case, however: the degree of occupation of soil surface area by microbes is about 0.1–0.2% and, moreover, the microbes form unevenly distributed colonies (Woldendorp, 1981). The scale at which microbes work suggests that they can best be studied at the level of the cell or colony. Combining the resulting data with the uneven distribution of the microbes could than give average respiration and denitrification data for a macroscopic part of the soil, e.g. thin soil layer. The objective of the aeration/denitrification study mentioned earlier, only demanded a measure for the consumption of oxygen at this higher scale of organization to calculate the degree of anaerobiosis, and for the consumption of nitrate and other intermediate electron acceptors. Therefore, it did not seem necessary to study the cell level in combination with the distribution of microbes over the soil surface area to obtain these bulk parameters. Instead, the objective of the study together with the level of organization of the biological processes led to the decision to model growth of biomass in relation to the availability of electron acceptors and organic matter for a thin soil layer. In this layer the underlying cell level and the effect of an uneven distribution of the microbes over the soil surface area are summarized in parameters such as an effective growth yield (kg of biomass-carbon kg^{-1} of organic matter-carbon) and an effective relative growth rate (μ, d^{-1}) that resulted from more detailed models (van Verseveld et al., 1977).

The process level of water flow in soil was chosen at the level of soil as a porous system, rather than at the pore level. Darcy's law gives a macroscopic description of soil water movement. Although this description of soil water movement is often considered to be based on first principles, Darcy's equation was found

empirically and the relationships between hydraulic conductivity and water content ($K-\theta$) and between the soil moisture tension and water content ($\Psi-\theta$) must be determined anew for each soil. Such characteristics thus integrate geometrial information on the pore system, the interactions among the clay platelets and water, and the macrostructure of the soil in the flow behaviour of water.

In both the description of the biological processes and the water flow process, the parameters (i.e. growth yield, μ, $K-\theta$ and $\Psi-\theta$) lump a number of aspects: they represent some kind of average. At present, measurements in soil can only be performed at this level, however, and in the light of the objective of the study it did not seem worth the trouble to detail the theories any further. These experimental aspects will be discussed further in Section 4.6.

4.4 Availability of theories

Agricultural simulation models integrate theories developed in various disciplines, particularly biology, physics and chemistry. Each separate theory, whether well-founded or merely a series of hypotheses, is based on a number of assumptions and is developed for a particular system. Often, the system considered is homogeneous, e.g. diffusion of gases in a continuum, or bacterial growth in a well-stirred continuous culture. The potential success of a theory when applied in the modeller's system can only be judged if the assumptions underlying the theory are thoroughly understood.

For example, models of soil respiration and denitrification require a description of diffusion of gases such as oxygen, carbon dioxide, nitrous oxide and molecular nitrogen in a porous medium, because among other things these gases determine the environmental constraints of these biological processes. Diffusion of gases is usually described by Fick's law, which assumes that transport of a gas is given by minus the product of its concentration gradient and a diffusion coefficient. This implies that each gas moves independently of the other gases. This last assumption needs further consideration. Diffusion is the process by which matter is transported from one part of a system to another as a result of random motions of molecules that have individual speeds of the order of 100 m s^{-1} (Marrero & Mason, 1972). The average displacement velocities of the gas, however, are much less: about 0.01 m s^{-1}. This large difference in velocities is caused by the collisions of molecules. Hence, diffusive fluxes of different gases in a mixture are coupled and the assumption of independent gas fluxes in Fick's law is just a rough approach to the diffusion process.

The rigorous gas kinetic theory, developed by Maxwell and Stefan (Hirschfelder et al., 1964), includes the coupling of gas diffusion fluxes. An interesting phenomenon that can be predicted very well with this theory is that when water evaporates from a water surface through a column of oxygen and molecular nitrogen, the latter gases are stagnant in the steady state situation, although they show concentration gradients (Toor, 1957; Leffelaar, 1987). If Fick's law is used

to predict fluxes from such concentration profiles, nonsense is produced: the order of magnitude of the calculated oxygen flux is similar to respiration measurements in the field (Leffelaar, 1987). The understanding of the assumptions of a theory is thus very important for proper modelling as well as for the correct interpretation of measurements.

Because the equations of Maxwell-Stefan and Fick are both available to describe gas movement, one has to choose between these models. If results for a specific system do not differ more than some preset fraction, there is no doubt that the simplest model should be preferred. The results of the Maxwell-Stefan and Fick equations for gas diffusion in soil were compared by Leffelaar (1987; 1988). For other process descriptions it is necessary to compare different theories before a proper choice can be made. Though necessary, this is sometimes, unfortunately, impracticable.

4.5 Possibility of clearly defining subsystems

To study a system and to develop models for it, the system must be clearly defined with respect to its environment. For this, boundaries should be chosen to isolate the system from its environment. Although system isolation may perhaps be approximated in the laboratory, it would certainly kill all field research if it were demanded for the field, because interactions between the system and its environment will always exist. Therefore, instead of trying to isolate a system, one should choose its boundaries in such a way, that it is possible to quantify the flows that result from the interactions or feedbacks between the system and its environment by taking measurements at these boundaries. Since measuring is expensive, the number of measurements at the boundaries should be minimized and the boundaries should be chosen so that the outside world may affect the system, but that the system hardly affects the environment. 'To achieve this, it may be necessary to choose a system that is larger than necessary for the original purpose', de Wit (1982a). It is an art to judge whether at a chosen boundary the flows that may result from the interactions or feedbacks from the system on the environment and vice versa are absent, or sufficiently small to be neglected, or whether these flows can be easily quantified by measurements. Only when flows that result from feedbacks are absent, negligible or measurable, can systems be reduced in size and can subsystems be studied separately. We may distinguish between geometrical or physical system boundaries and process boundaries.

In the case of the aeration/denitrification study, thanks to a specially designed laboratory respirometer system, in which homogeneous, cylindrical, soil aggregates can be studied (Leffelaar, 1986), it was possible to choose a geometrical boundary that isolated the system. Thus, an experimental reality was created that had the advantage of enabling a simulation model to be developed for the same geometry. The experimental system thus precluded any speculation about form of the aggregates and contact areas between aggregates as they occur in the field from the discussion about the comparison of the experimental and theoretical

results of the aeration/denitrification study: the comparison of results could therefore focus on the causal relationships affecting denitrification, as intended (Leffelaar, 1988). The disadvantage of such a laboratory system may be the difficulty of comparing the results with the field scale, but this was not the objective of the study.

The processes, each with their approximate time coefficients, that can be distinguished in the denitrifying system are biological respiration and denitrification, and the transports of water, solutes and gases, as depicted in Figure 20. Each of these processes is complex and involves different disciplines. Hence, one would like to first study each process separately before it is possibly integrated into a larger model, and again we are confronted with the problem of how boundaries should be chosen, but now at the process level. For process boundaries, the same rule applies as for system boundaries: flows that result from feedback mechanisms should be absent, negligible or measurable. Therefore, we should first examine if interactions between the processes mentioned exist. By way of illustration two such examinations follow below, one with regard to gas and water transports and one with respect to the environment and microorganisms.

4.5.1 Feedback mechanisms of water content on gas transport

The amount of water in soil affects the cross sectional area that is available for transport processes via the gas-filled pore space and the gas continuity of pores. Water also affects the length of the path (tortuosity) that is to be travelled by a substance, both for the water phase and the gas phase. The change of water content directly influences the transport of gases, because the total gas pressure increases at the site where water content increases. Permanent pressure differences are unlikely to exist at short distances apart, though, because a change in water

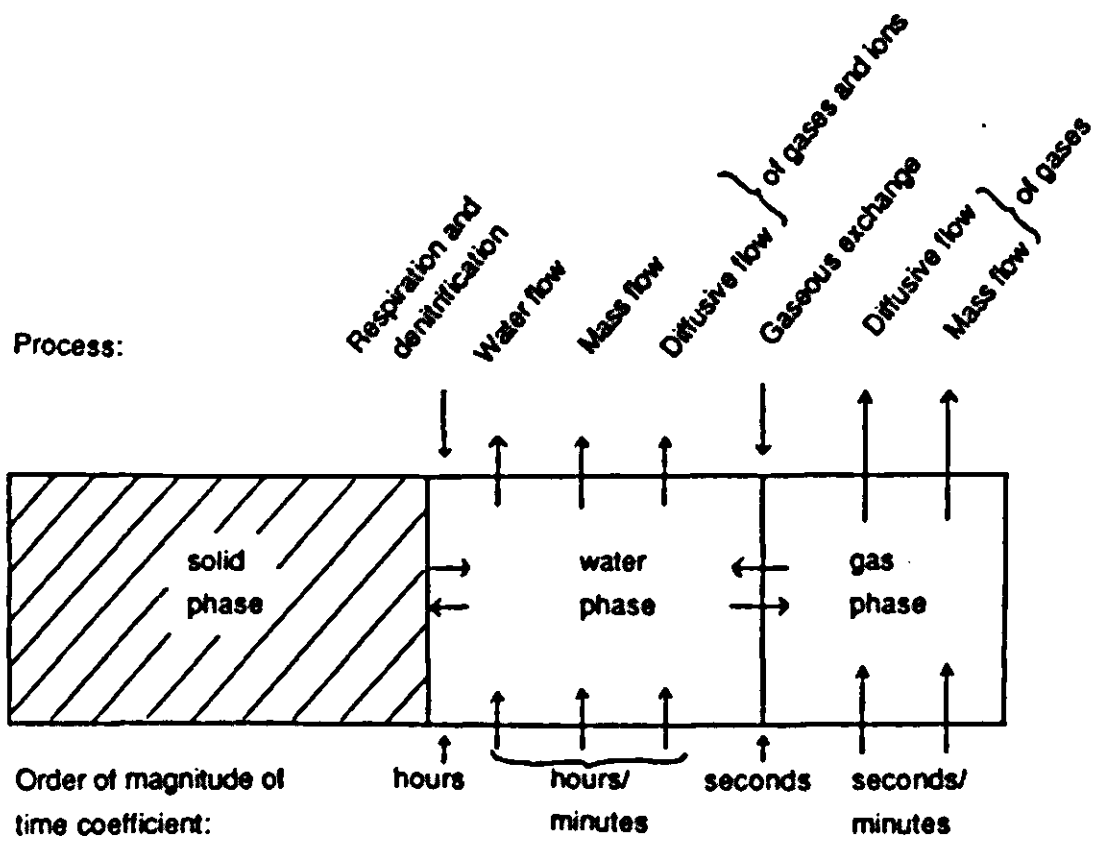

Figure 20. Processes distinguished in one soil layer of the aeration/denitrification model, with their approximate time coefficients.

content causes a countercurrent of gas: thus mass flow and mixing occur and the total gas pressure usually does not change. Besides, each gas has a different solubility in water. Thus, if gas composition changes, the total gas pressure changes, which also induces a mass flow of gas. At the same time, dissolved gases are carried along with the water, and gas diffusion takes place through the water phase and the gas phase.

Since the flows of matter that result from these feedback mechanisms are neither negligible nor measurable (at present), an accurate description of gas transport in soil is only possible when soil water movement is taken into account. Still, the gas flow model can be tested for the situation of water being stagnant or in the extreme condition of a dry soil (Leffelaar, 1987), but it is clear that in this situation not all feedbacks are included and certain interactions could be overlooked.

4.5.2 Feedback mechanisms of the soil environment on microorganisms

Soil water content affects the concentrations of substrates and electron acceptors as experienced by the microorganisms in soil. It is expected that these concentrations, rather than the corresponding amounts, affect microbial growth and maintenance. Water further affects the possibilities for transport (by diffusion, mass flow and hydrodynamic dispersion) of dissolved substrates, of electron acceptors and of microorganisms – if these are not attached to soil particles. At higher water contents microorganisms may be (more) mobile, which enhances their chance of survival. At low water contents microgradients of substrates around colonies may develop and microorganisms might not obtain enough food. Furthermore, soil water potential may affect the activity of microorganisms (Griffin, 1981). This implies that both soil water content and soil water tension are needed to elucidate problems of soil biology such as denitrification. If gaseous electron acceptors have a low solubility in water, fewer electron acceptors are available for the microorganisms, if one assumes that microorganisms live in the soil water phase. Finally, soil pores form niches for microorganisms, protecting them from predators. These feedback mechanisms of environmental conditions on soil microorganisms are neither negligible nor measurable at present, so that isolating microorganisms from their soil environment with the aim of studying them separately, gives results that are not applicable to the real soil. As in the case of the gas model, it is possible to test the respiration/denitrification model under the condition that water, substrates, electron acceptors and microorganisms are homogeneously distributed in the soil, e.g. by working with a very thin soil layer in which it may be supposed that gradients and thus transport processes are absent (Leffelaar & Wessel, 1988). It is not possible, however, to exclude the influence of soil water tension and gaseous solubility on the biological processes that occur in the thin soil layer.

Both for the gas model and for the aeration/denitrification model the proposed study of the simplified system is only meaningful if the simplified system behaves

similar to the system as a whole.

The existence of many feedback mechanisms between microorganisms on the one hand and the environment on the other hand, means that biological and physical processes in the soil need to be studied in conjunction with each other. Similarly, soil biology parameters must be determined in the environment in which they should apply, not only because of the feedbacks mentioned, but also because organisms adapt themselves to a new environment. One such soil-biology parameter, whose value when measured in soil differs significantly from its value measured in pure cultures, is the half saturation value in the Monod equation. This parameter was found to be higher in soil than in pure culture studies (Firestone, 1982), apparently because some kind of mass transfer is involved (Shieh, 1979), e.g. diffusion on a microscale. The feedback mechanisms mentioned were partly discovered by combining the different submodels of the processes mentioned into a large simulation model (Leffelaar, 1988). Thus, the coupling of the processes and the explicit documentation of the (theoretical) interactions brought soil ecology research a step forward. In fact, the coupling action is the only new element in the application of biological and physical knowledge to solve the aeration/denitrification problem: Fick's law was reported in 1855, based on the analogy with the description of heat flow by Fourier (1822), Darcy's law was discovered in 1856 for saturated soil (but in 1931 Richards concluded that Darcy's law could also be applied to unsaturated water flow), Maxwell and Stefan presented their gas kinetic theories in 1867 and 1871/1872, respectively, and Monod's equation was launched in 1942, based on work by Michaelis and Menten (1913).

4.6 Possibility of validating the model of a system

Sometimes models need not be validated if they are based on well accepted (usually previously validated) theories and if they are exclusively applied to a type of system similar to the one for which the theory was developed. Models of ecological systems will, however, always need validation, not only at the level of the integrated model but also at the explanatory level, i.e. the submodels and processes. There are at least two reasons for this.

Firstly, results on the explainable level may compare very favourably with experimental data, whereas the underlying processes are not well simulated. This is demonstrated in Figures 21 and 22. Figure 21 shows the experimental and simulated time courses of the oxygen pressures in the centre and 4 cm from the centre of the experimental aggregate in the aeration/denitrification study, and the increase of nitrous oxide and molecular nitrogen in the chamber that contains the aggregate. The oxygen pressure curves show satisfactory agreement with the experimental findings. Simulated losses of nitrous oxide and molecular nitrogen lag behind the experimental curves, but the qualitative resemblance is reasonable. Figure 22 shows the distribution of nitrate in the experiment and in the simulation: these distributions are almost mirror images! Hence, the combined study of

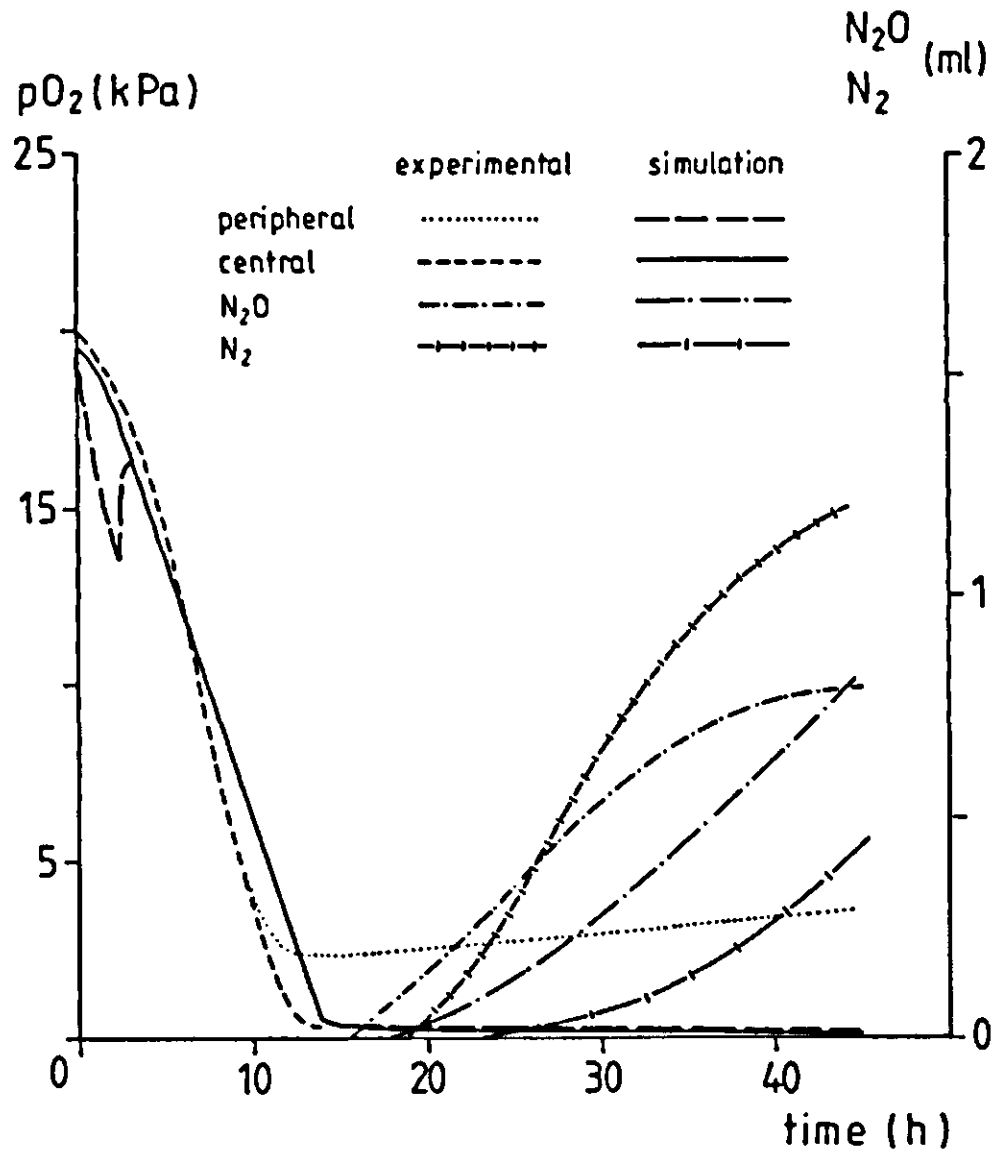

Figure 21. Simulated and experimental oxygen pressure (left *y* axis) in centre and 4 cm from centre (peripheral) of soil aggregate and volumes of nitrous oxide and molecular nitrogen in chamber that contains the aggregate (right *y* axis) as a function of time (Source: Leffelaar, 1988).

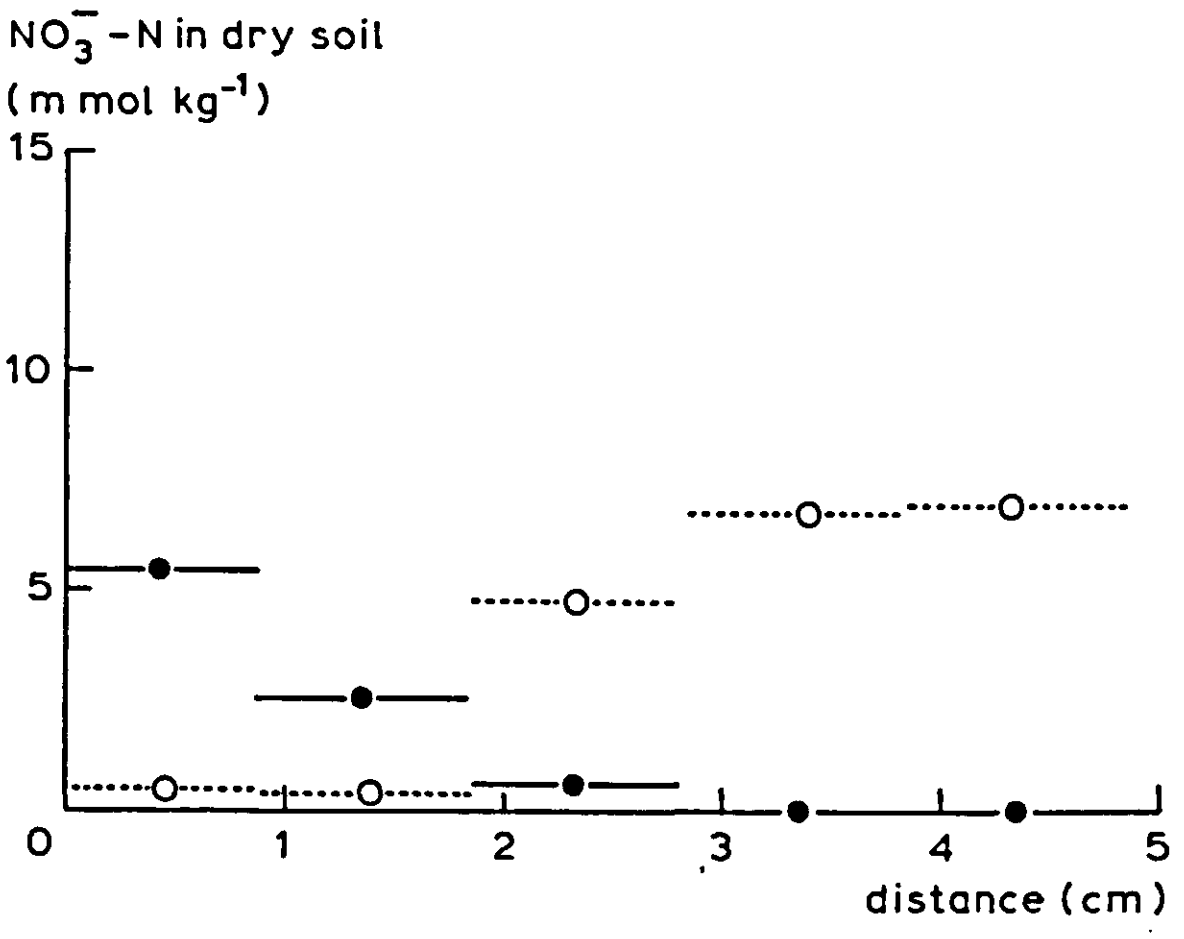

Figure 22. Simulated (——●——) and experimental (---o---) distributions of nitrate in a cylindrical soil aggregate (centre at 4.9 cm) after 45 hours (Source: Leffelaar, 1988).

experiment and simulation reveals that parts of the processes are not correctly described, implying that a hypothesis is not valid, or that some of the measurements may be suspect. Further study is then needed.

The second reason to validate models at the explainable level and at the explanatory level is that the quality of biological and physical models is usuallly not the same, because biological processes are more complex than physical processes. The description of the biological processes of respiration and denitrification on the basis of growth, first order rate constants, yield factors, maintenance coefficients, and so on, was founded on many more assumptions than the description of water flow (Leffelaar & Wessel, 1988). The quality of models is thus reflected by the number of assumptions or 'non-binding opinions' (de Wit, 1970) underlying the rate equations: more assumptions mean more possibilities of introducing inaccuracies, and less quality of the model description. Nevertheless, models of different quality need to be coupled, simply because problems that contain aspects that are known to various degrees of detail must be solved; ecological research would be seriously hampered if models of similar quality had to be developed first.

As indicated above, the physical model for water flow is less complicated than the model for the biological process. On the one hand, this is because empirical relationships between the hydraulic conductivity and water content and between the matric suction and water content are used in Darcian water flow models (see Section 4.3). On the other hand, it is assumed that the soil is homogeneous and rigid: cracks, aggregates or other structures are absent and no swelling or shrinking occurs.

Model validation implies that the modelled state variables can be measured as a function of time. The more detailed the model description, the more difficult the measurements that need to be performed (see Section 4.7). For example, microorganisms in the soil pores will experience a certain oxygen pressure and water tension. Although a polarographic oxygen electrode that might be used to monitor the oxygen pressure in soil may have a diameter as small as 0.5 mm, this is still very large compared with the pore diameter of about 0.03 mm at field capacity. When the reaction of microorganisms to moisture tension is to be evaluated, it is only possible to measure on the 'tensiometer scale' having a surface area in the order of cm^2. Both the oxygen sensor and the tensiometer thus seriously disturb the environment in which the processes take place and, moreover, they yield integrated results over space. Such average experimental results, which include the feedbacks mentioned before, apply at a higher level of organization than the cell level where the process of respiration actually occurs. In view of these experimental restrictions, it seems most appropriate to model such a process at the same level of detail as it can be measured. This means that average parameters are used to characterize the respiring soil organisms, and that it is assumed that this is permissible because the process considered is distributed fairly homogeneously throughout the soil and that the process will show a linear dependence on these average parameters. Field measurements, however, usually

show a large variability. When models are parameterized with average parameters, one should therefore not be surprised about deviations from reality. In fact, the calculations should be performed with a number of point-measured parameters under the assumption of homogeneity and thereafter the field average should be calculated, using the additional information on how the parameters are distributed over the field (de Wit & van Keulen, 1987). A sound description of soil heterogeneity is thus needed, and in this respect, the work of Rappoldt (1990) is promising.

4.7 Possibility of returning to the field level of organization in the systems synthesis phase

Suppose detailed validated models are available that describe a number of different processes of a subsystem and that explain system behaviour satisfactorily. To proceed to the field level would imply that a gap of several orders of magnitude must be bridged both for the spatial scale, i.e. from centimetres to hectometres and for the time scale, i.e. from days to seasons, and this comes on top of the range of orders of magnitude that is already incorporated in the detailed submodels. Is such an extension possible in principle and is it necessary?

4.7.1 The possibility of proceeding from detailed models and/or submodels to the field scale

Models need to be initialized and parameterized and submodels need to be coupled. Models usually contain negative feedback mechanisms that result in stable equilibria after some time. For models of natural systems, where one is often interested in the behaviour of the model after a perturbation of the equilibrium situation, equilibria should be independent of the initial conditions. Therefore, initialization need not be very accurate, but the experiments with the model should begin after a simulation period that is sufficiently long to allow the model to reach such an equilibrium (which is mostly dynamic).

In production systems, however, one is interested in the time course of the state variables from a start position to the equilibrium (which is mostly static); for instance, crop growth ending in crop maturity. Because different initializations will give different time courses towards equilibrium, the initialization of models describing production systems must be done with care. Furthermore, when a system can reach different states of equilibrium, which state is reached will depend on the initial conditions. This may happen in the competition of crops and weeds for light (Spitters & Aerts, 1983). To initialize a model, the values of all the state variables should be determined within a short time span in which they do not change materially (de Wit, 1982a). This might present practical problems if a number of levels of organization with their concomitant time coefficients were bridged within one model.

Model parameterization for the models of natural systems and of production

systems should always be done with care, because the parameter values largely determine model behaviour.

When coupling models, the relative magnitude and the (experimental) uncertainty of states and rates should be reconsidered, to assess whether model coupling will yield a reasonable integrated model. Suppose that two separate models exist, one for grass and one for earthworms. Both models calculate the dynamics of the amount of carbon in the grass and in the earthworms. In each model the state variable of the amount of carbon is important, but will this also be true if these models are combined? To judge this, let us first compare the state variables, i.e. the amounts of carbon. If the amounts of carbon are, for instance, 99 for the grass and 1 for the earthworms, one would consider neglecting the latter in a combination model.

A second consideration when judging the meaningfulness of model coupling is to compare the rates of change of the carbon states or carbon turnover rates, which, when combined with the values of the carbon state variables also give information about the related characteristic times or time coefficients of the models. If the carbon turnover in the earthworms was very high compared with the carbon turnover of the grass, one would like to take the earthworms into account in the combination model. The accuracy of determination of the carbon state of the earthworms could be much lower than for the grass, however, because of difficulties in collecting worms. This could create unacceptably large differences in accuracy of initialization in the combination model. Pool size, turnover rate and accuracy of determination of state variables and related parameters should be considered when knowledge is to be integrated in combination models.

It is probable that for a given system there is an optimum number of state variables or processes that should be included in a model. This is illustrated in Figure 23, where the number of state variables or processes in a model is given on the x axis and the approximation of reality on the y axis. Adding processes before the optimum is reached will improve the model's applicability, because systems reality is better approximated. Systems reality will never be reached, however, because de Wit's statement from 1970 that 'we know only bits and pieces of nature around us' remains valid. Taking more processes into account than the optimum number would give problems of initialization, parameterization and accuracy, but moreover, the researcher might lose his overview of the problem he wanted to clarify. Above the optimum number of processes one would like to consider the model as a system, to subsequently simplify or model it.

Unfortunately, it does not seem possible to determine the optimum number of processes in a model as depicted in Figure 23; finding the optimum remains an art. Also, the number of different orders of magnitude in level of organization that can be bridged at this optimum is still unresolved.

These general problems with respect to initialization, parameterization, coupling of models and finding an optimum of processes to be included in explanatory models would, when solved in terms of general operative rules, considerably advance research in soil ecology, even without building the models, but until

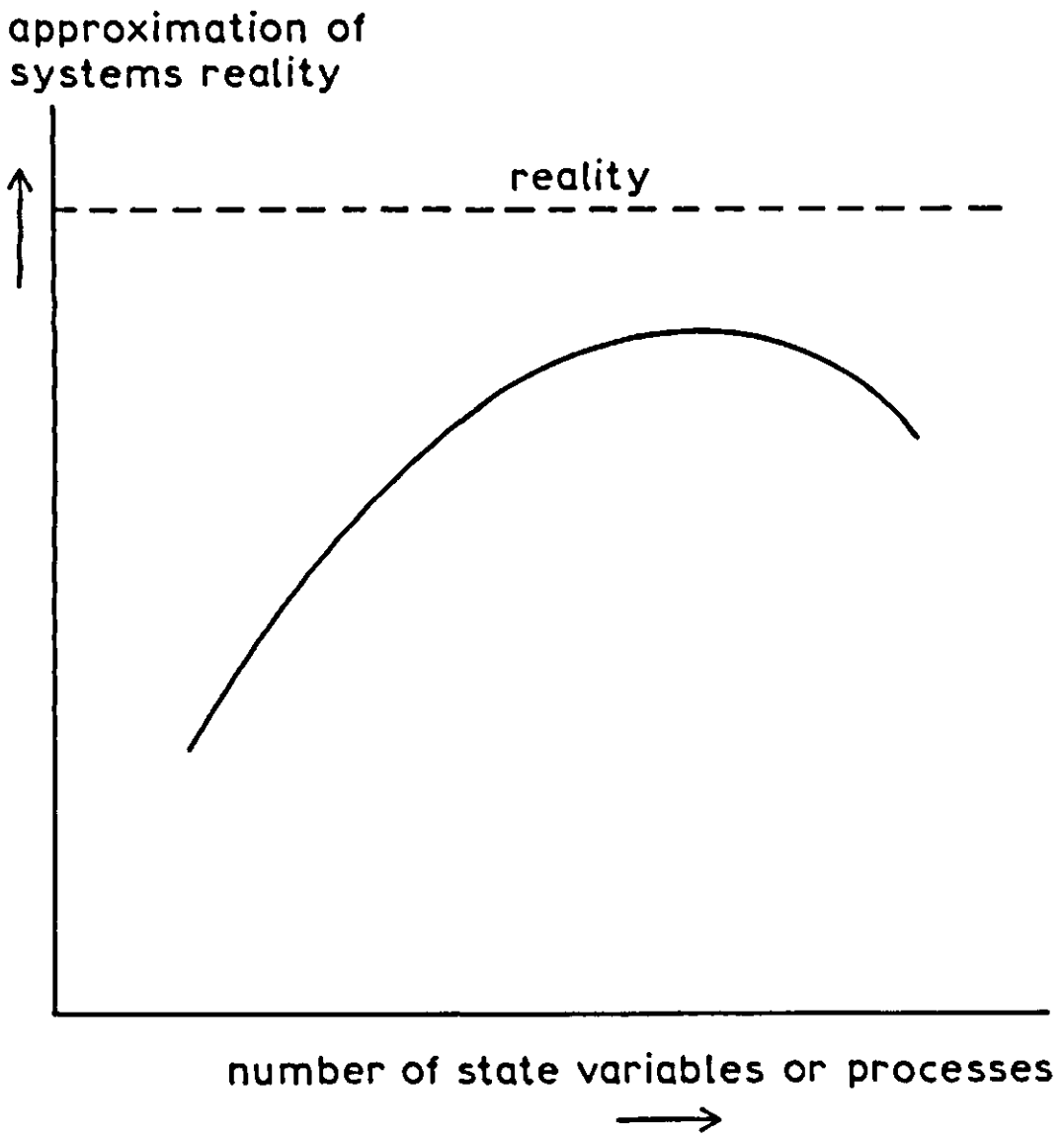

Figure 23. Qualitative relationship between the number of state variables or processes included in a model and the approximation of systems reality.

that time common sense, experience and trial and error must be practised.

4.7.2 The necessity to proceed from detailed models and/or submodels to the field scale

Sometimes it may be possible to proceed from the detailed level of organization directly to the integrated level, when concepts of thinking from small-scale studies happen to apply to the larger field scale. Then, manageable characteristics are directly derived from the small-scale study, and applied at the field scale. For example, the aeration/denitrification processes occur in a similar cause and effect relationship in the field as in the small-scale experimental and model studies. Therefore, it would not be unlikely that conclusions from the detailed study could be directly applied to the field. Indeed, nitrogen losses in the laboratory experiments (Leffelaar, 1988) were of similar magnitude to those reported by Rolston et al. (1976; 1978) and Colbourn & Dowdell (1984) for the field.

Another striking example of the direct use of a small-scale process to the field scale is the process of photosynthesis, which occurs at the chloroplast level with characteristic length and time scales of 1 μm and 10 ms (van Kooten, 1988). The process at the chloroplast level is directly responsible for the crop production process, and explanatory crop growth models start with a description of photosynthesis (de Wit, 1965).

When conclusions applying to the field level can be drawn from more detailed work, the level of integration in the detailed study is already sufficiently high. In other words: it may be that the field scale of say 100 by 100 m is not the smallest unit that contains all different subsystems and subprocesses with respect to the aeration/denitrification process. A square metre or even less might be sufficient.

4.8 Concluding remarks

The modelling of systems is an admission that we cannot understand systems fully and as a whole. The systems analysis and synthesis approach can be exploited best if this admission is translated into real simplifications, rather than by trying to split up an ecosystem into all its composing subsystems, with the purpose of modelling each subsystem and of interconnecting all submodels. This implies that no general purpose models can be built (de Wit, 1970).

It is very likely that the better a system is understood, the more simply it can be represented in a model (Cole et al., 1983), because the major state variables and feedback mechanisms are known.

Coupling of processes and submodels that influence each other will advance ecological research because:

- the coupling assumptions need to be formulated explicitly
- the coupling will expose shortcomings in our knowledge
- by including more processes in a model, it may be concluded from sensitivity analysis that it is not strictly necessary to incorporate some of these processes to get a better understanding of the system. In the coupling process different scientific disciplines will meet.

Agricultural models need to be validated or tested with respect to each different process modelled (if possible), since the overall model results may be good because of compensating negative feedback mechanisms, whereas intermediate results are not well described.

To determine if a soil organism or a process can be studied separately from its environment, with the purpose of using the results subsequently in the system from which it was separated, the possible feedback mechanisms should be listed and judged beforehand.

We still cannot say much in general about the number of subsequent levels of organization that can or should be bridged in a model. If a model involves time coefficients of different orders of magnitude, a stiff-equation problem exists. This may give rise to excessive number crunching. De Wit (1982b) stated that this should be avoided in simulation programs for digital computers by restricting the number of levels of organization that are incorporated in one simulation model. Present-day computers are very fast, however, and this number crunching should no longer be the prime reason for restricting the number of levels of organization. Rather, a possible restriction should be judged in terms of whether including another level of organization would sufficiently increase causal insight in the system and, if so, whether no problems with the initialization and parameter-

ization are expected. To this end a pragmatic method of trial-and-error must be applied.

Research should aim to discover laws that integrate detail to acceptable levels (de Wit, 1968). Models can be very helpful in this process: they can be used to investigate if model results can be summarized in a single number or in simple equations (Penning de Vries et al., 1974; Goudriaan, 1977).

Most natural systems are heterogeneous, implying that average parameters do not often characterize the system. For example, there is no average aeration status of soil when anaerobiosis and aerobiosis coexist. In such cases it is more informative to measure with a certain strategy, rather than to perform measurements at random.

Modelling remains largely based on common sense and experience. Modelling thus remains an art, rather than a science. A unique art, though, with strong practical and theoretical possibilities and results.

4.9 Acknowledgments

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